Simulations and DM Searches: Some Discussion Starting Points

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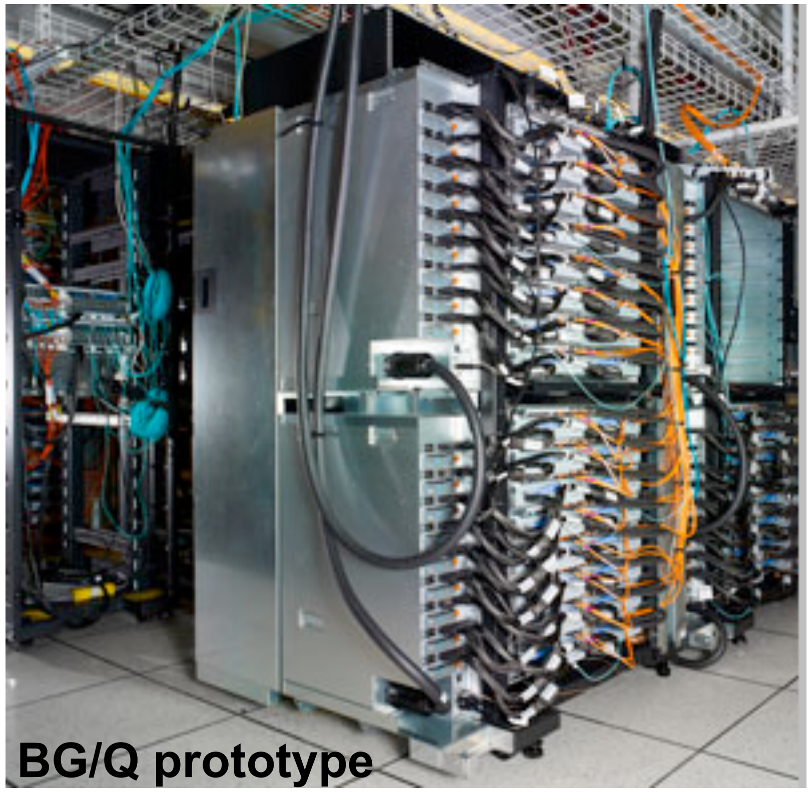
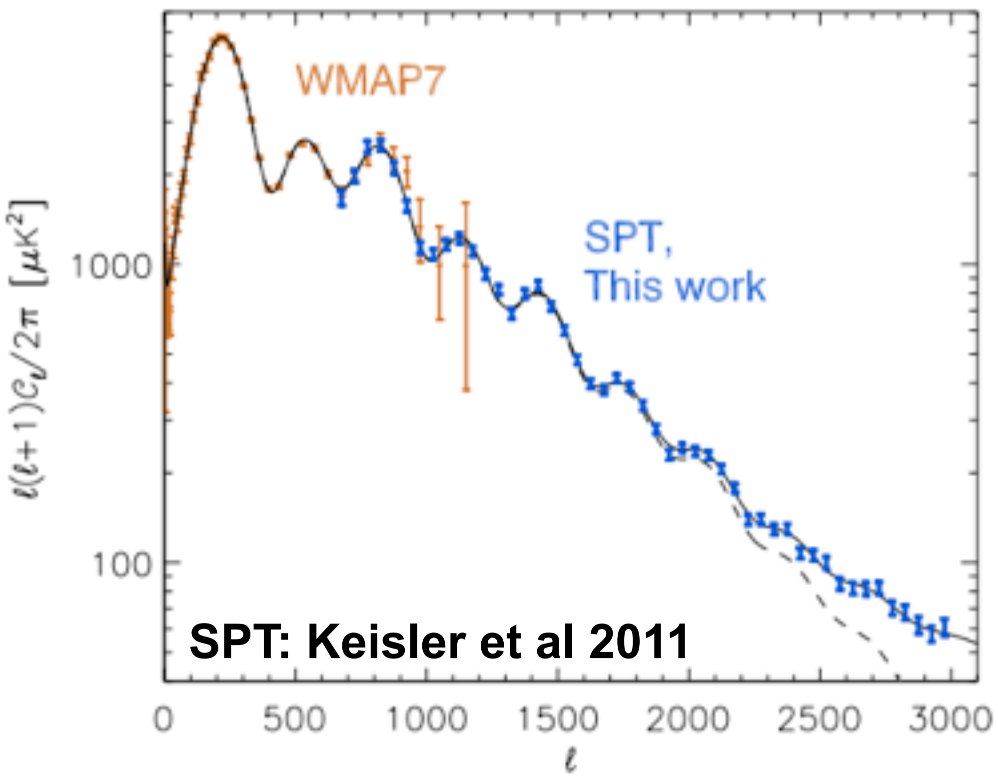
Boundary Conditions/Outline

- **I am not an expert on this subject! This talk is mainly meant to spark discussion by other people ;-)**
- **Dark Matter Searches:**
  - Direct -- scattering of a passing WIMP with a nucleon, needs massive detectors, excellent background rejection
  - Indirect -- search for anihilation signal (photons, neutrinos, antiparticles); large/sensitive detectors again
  - Special cases -- axions, sterile neutrinos, others (will not cover except in passing)
  - LHC -- new particles that could be DM (will not cover)
- **Theory Status:** Many ideas/possibilities, see theory talk
- **Experimental/Observational Status:** Controversial/ exciting, see theory and experiment talks



Particle Physics vs. Astro/Cosmology

- **Precision Cosmology: Something very close to CDM fits all data that we consider to be ‘precision’**
- **Disentangling particle physics and astro/cosmology:**



Interaction rate as a function of energy

Direct --
$$\frac{dR}{dE} = \left[\frac{\sigma_N F_N(E)}{2m_\chi m_r^2}\right]\left[\rho\int_{v_{min}} f(v)\, d\ln v\right]$$

$$m_r = m_\chi m_N/(m_\chi + m_N)$$

Flux of annihilation products

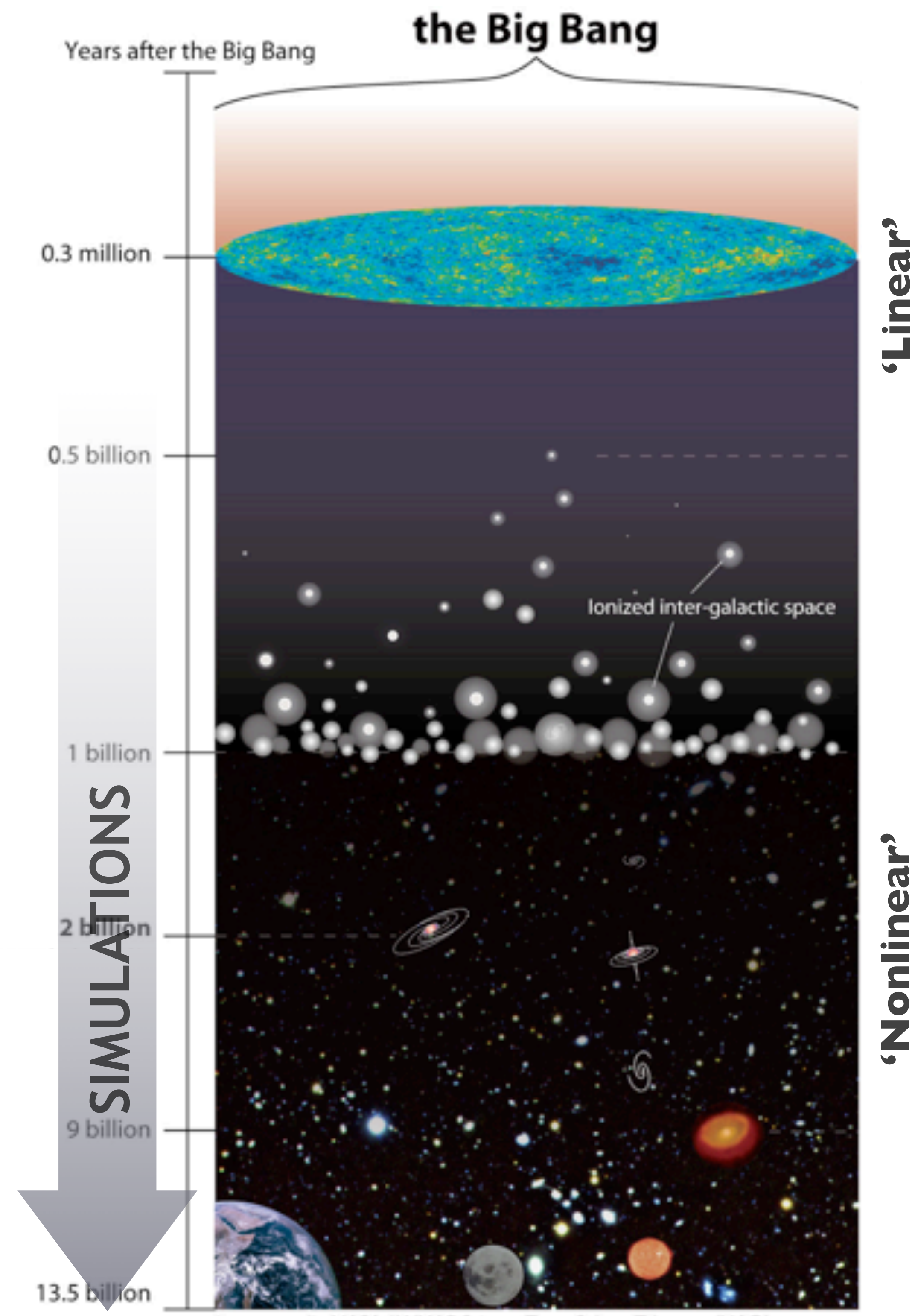
Indirect --
$$\frac{d\Phi}{dE} = \frac{1}{4\pi}\left[\sum_i \frac{\langle\sigma v\rangle_i}{m_\chi^2}\frac{dN_i}{dE}\right]\left[\int_{LOS}\rho^2(l)\,dl\right]$$

(i) Must rely on simulations and modeling to determine the DM density, velocity distribution and substructure. How hard is this?

(ii) Must model annoying astrophysics (not covered)

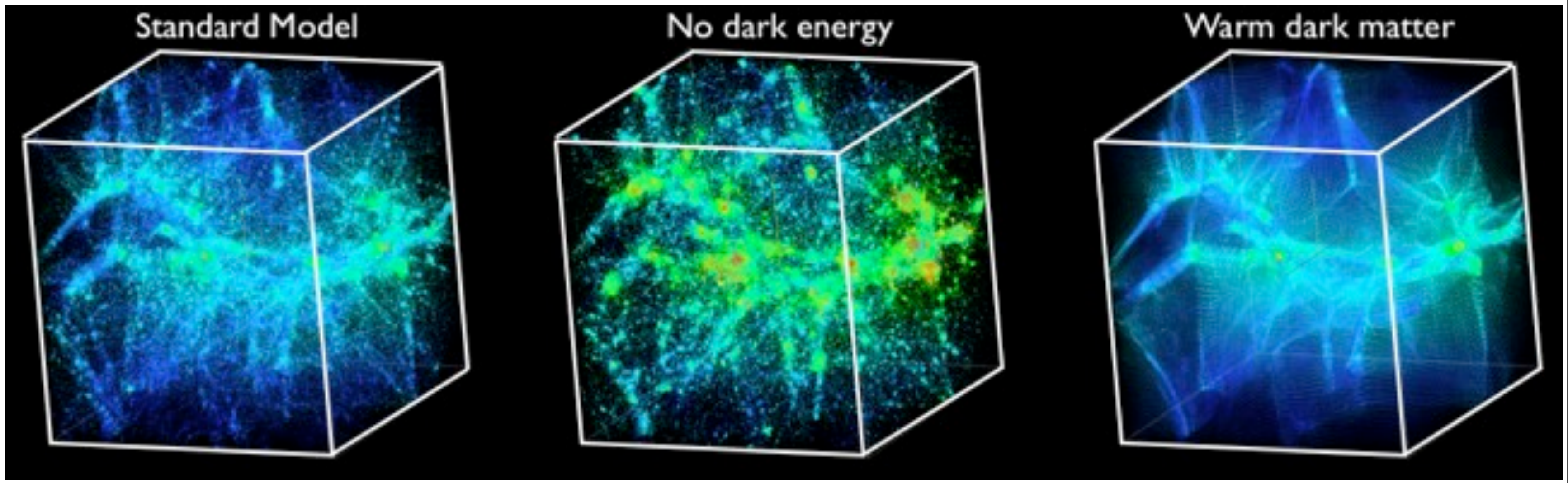
Structure Formation: The Basic Paradigm

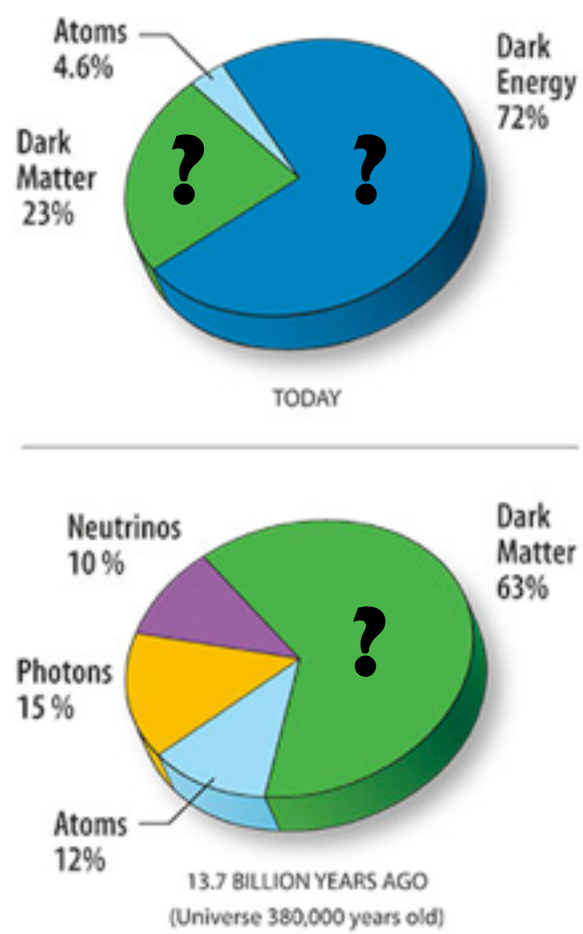
- **Solid understanding of structure formation; success underpins most cosmic discovery**
  - Initial conditions laid down by inflation
  - Initial perturbations amplified by gravitational instability in a dark matter-dominated Universe
  - Relevant theory is gravity, field theory, and atomic physics (‘first principles’)
- **Early Universe:** Linear perturbation theory very successful (CMB)
- **Latter half of the history of the Universe:** Nonlinear domain of structure formation, impossible to treat without large-scale computing



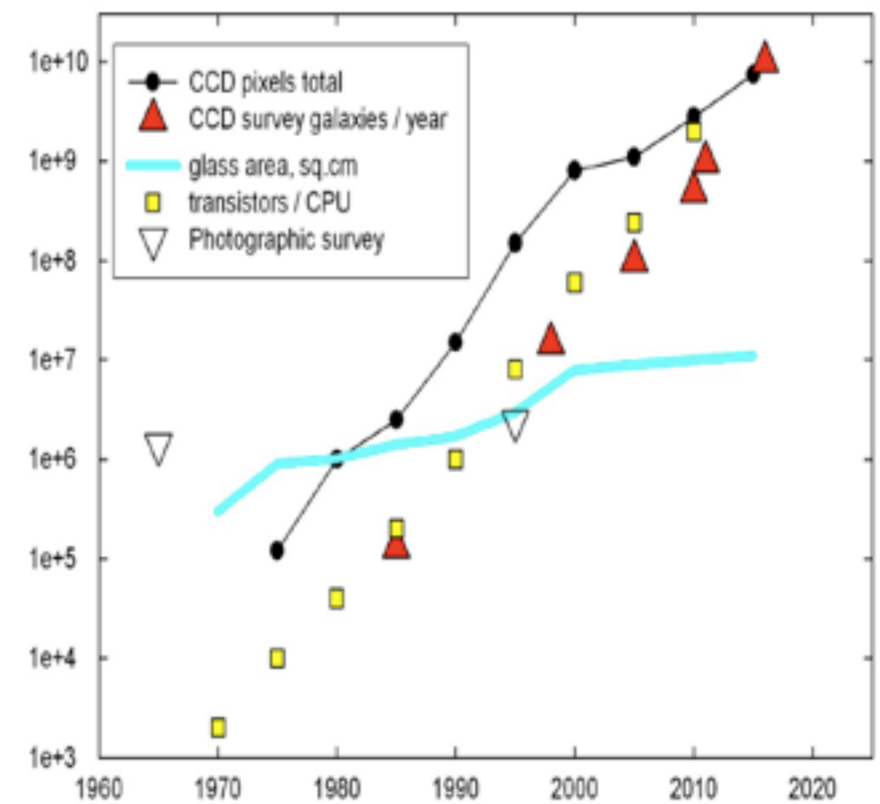
Precision Cosmology: The "Low-Resolution" Sky

- **Cosmological Probes:** Measure geometry and presence/growth of structure
- **Examples:** Baryon acoustic oscillations (BAO), cluster counts, CMB, weak lensing, galaxy clustering, --
- **Standard Model:** Verified at the 5-10% level across multiple observations
- **Future Targets:** Aim to control survey measurements to the ~1% level, can theory and simulation keep up?





Cosmic content pie charts



Optical survey 'Moore's Law': Statistics not a problem: opposite of DM searches!

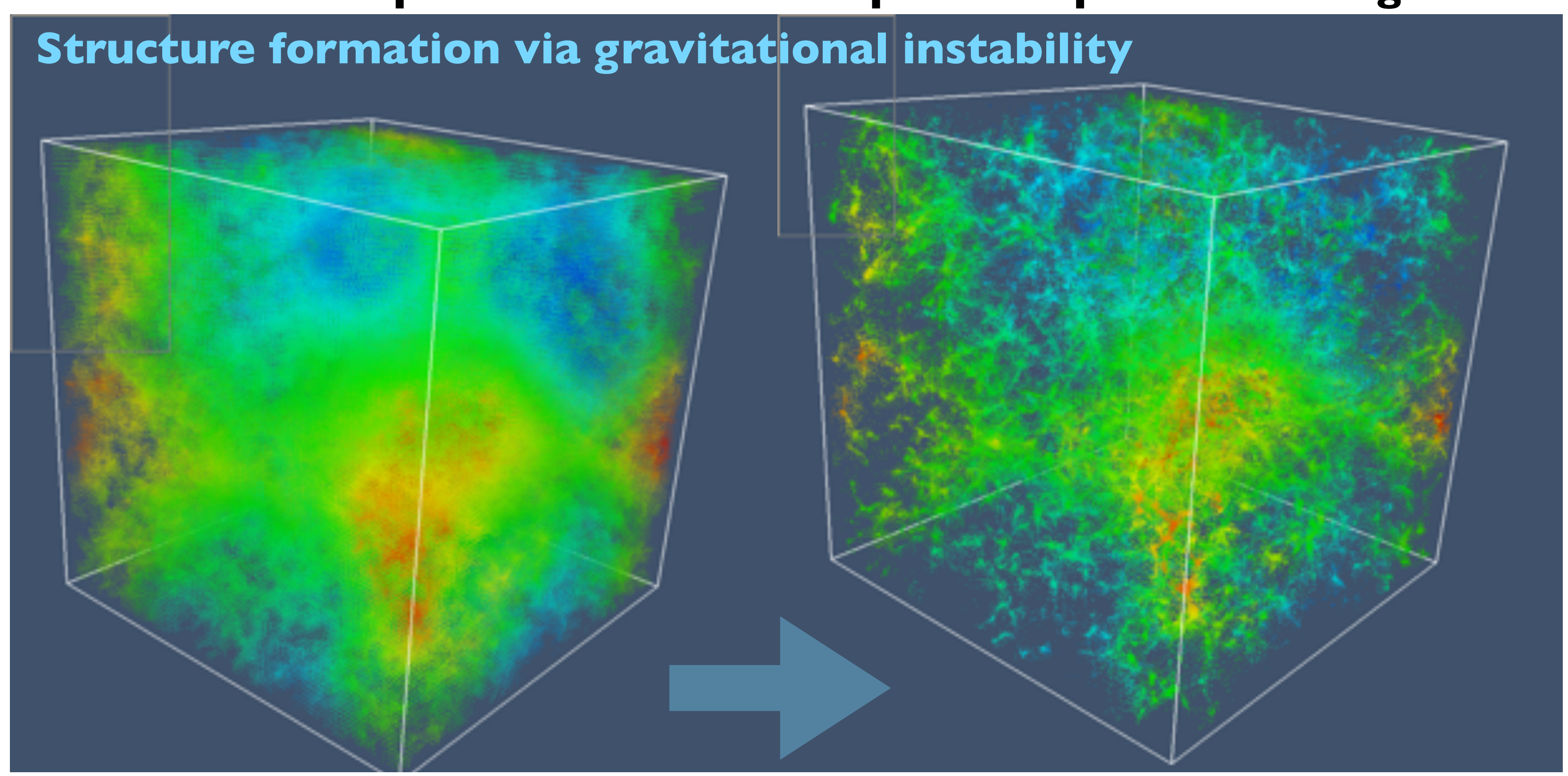
Cosmological Simulations

- Gravity dominates at large scales, **key task: solve the Vlasov-Poisson equation (VPE)**
- VPE is 6-D and **cannot be solved as a PDE**
- N-body methods; gravity has (i) **no** shielding but is (ii) **naturally** Lagrangian
- Are errors **controllable**?
- At smaller scales add gas physics, feedback, etc. **(subgrid modeling inevitable)**

$$\frac{\partial f_i}{\partial t} + \dot{\mathbf{x}}\frac{\partial f_i}{\partial \mathbf{x}} - \nabla\phi\frac{\partial f_i}{\partial \mathbf{p}} = 0, \qquad \mathbf{p} = a^2\dot{\mathbf{x}},$$

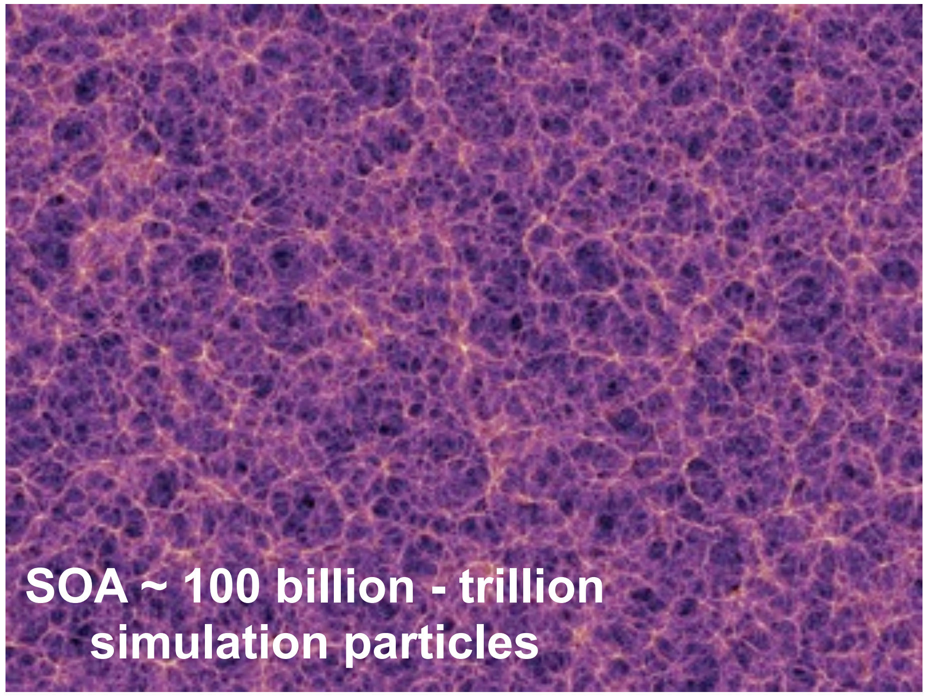
$$\begin{aligned}
\nabla^2\phi &= 4\pi G a^2(\rho(\mathbf{x},t) - \langle\rho_{\rm dm}(t)\rangle) \;=\; 4\pi G a^2\Omega_{\rm dm}\delta_{\rm dm}\rho_{\rm cr},\\
\delta_{\rm dm}(\mathbf{x},t) &= (\rho_{\rm dm} - \langle\rho_{\rm dm}\rangle)/\langle\rho_{\rm dm}\rangle),\\
\rho_{\rm dm}(\mathbf{x},t) &= a^{-3}\sum_i m_i \int d^3\mathbf{p} f_i(\mathbf{x},\dot{\mathbf{x}},t).
\end{aligned}$$

Cosmological Vlasov-Poisson Equation: A 'wrong-sign' electrostatic plasma with time-dependent particle 'charge'

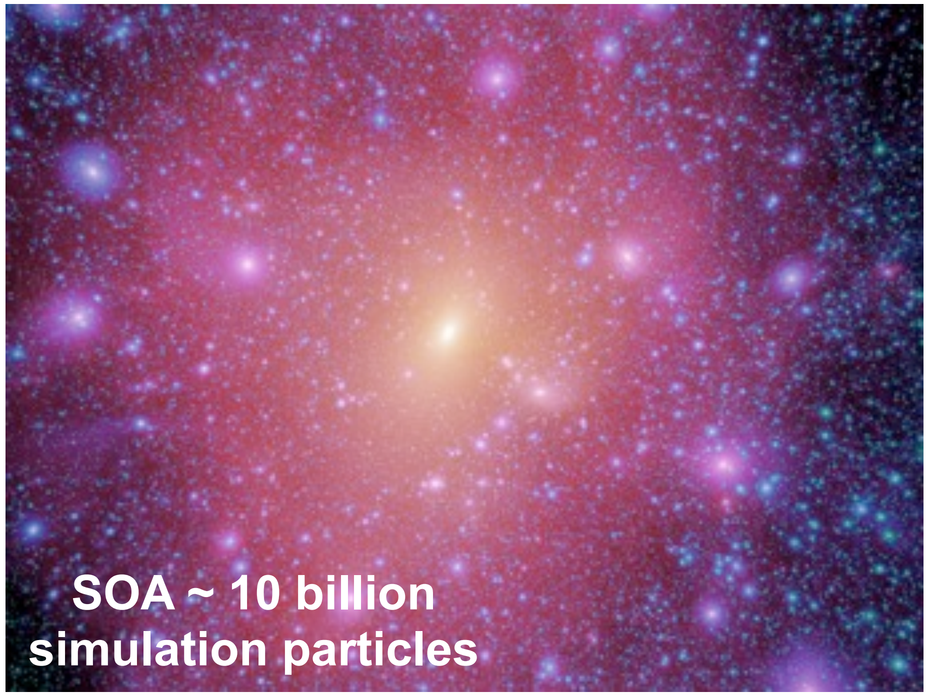


Dark Matter Simulations

- **Precision Probes:** Smallest length scales typically >0.1-1 Mpc; observation/physics systematics hopefully controllable to order unity (by definition -- otherwise its not precision!)
- **Dark Matter Searches:** Smallest length scales typically <<1 Mpc; poor observational S/N, serious problems with modeling systematics
- **Simulation Types:** Hence we have two types of simulations: (i) large volume, high-statistics, and (ii) small volume, very high-resolution
- **Difficulties:** Simulations of type (i) characterized by scalability requirement, of type (ii) by performance requirement (more painful?)
- **Gastrophysics:** Simulation campaigns somewhat more justified in case (i), modeling estimates a bit more in case (ii) (true in general)



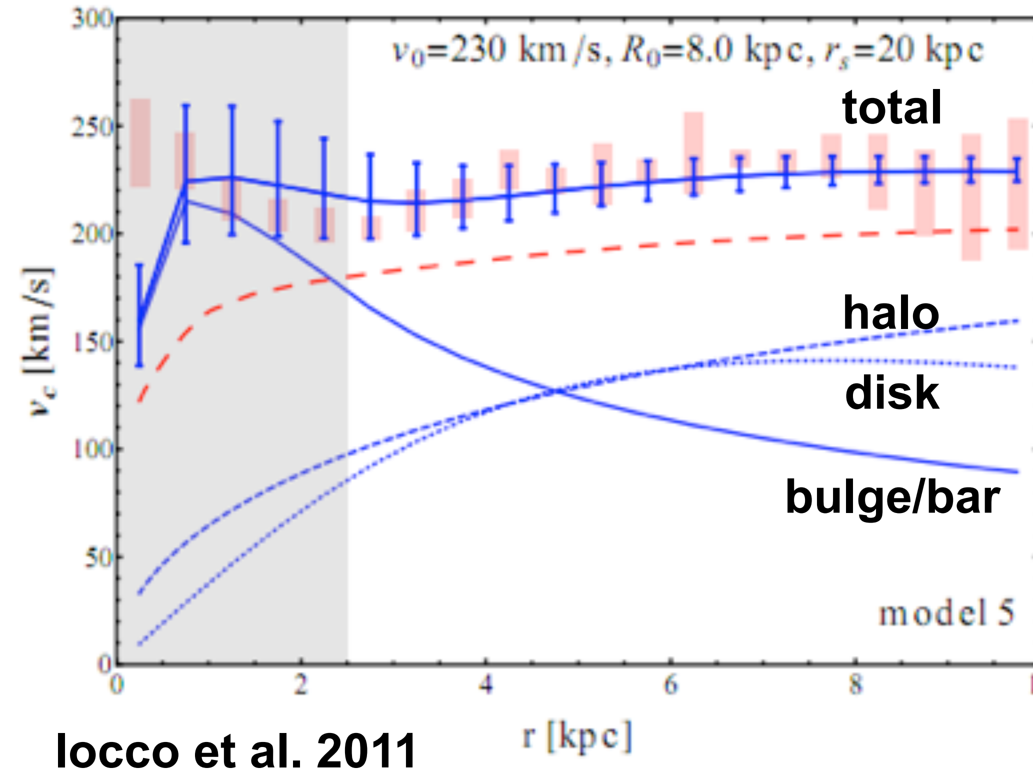
Millennium run, res~10 kpc, 10 billion particles, 500 Mpc/h comoving



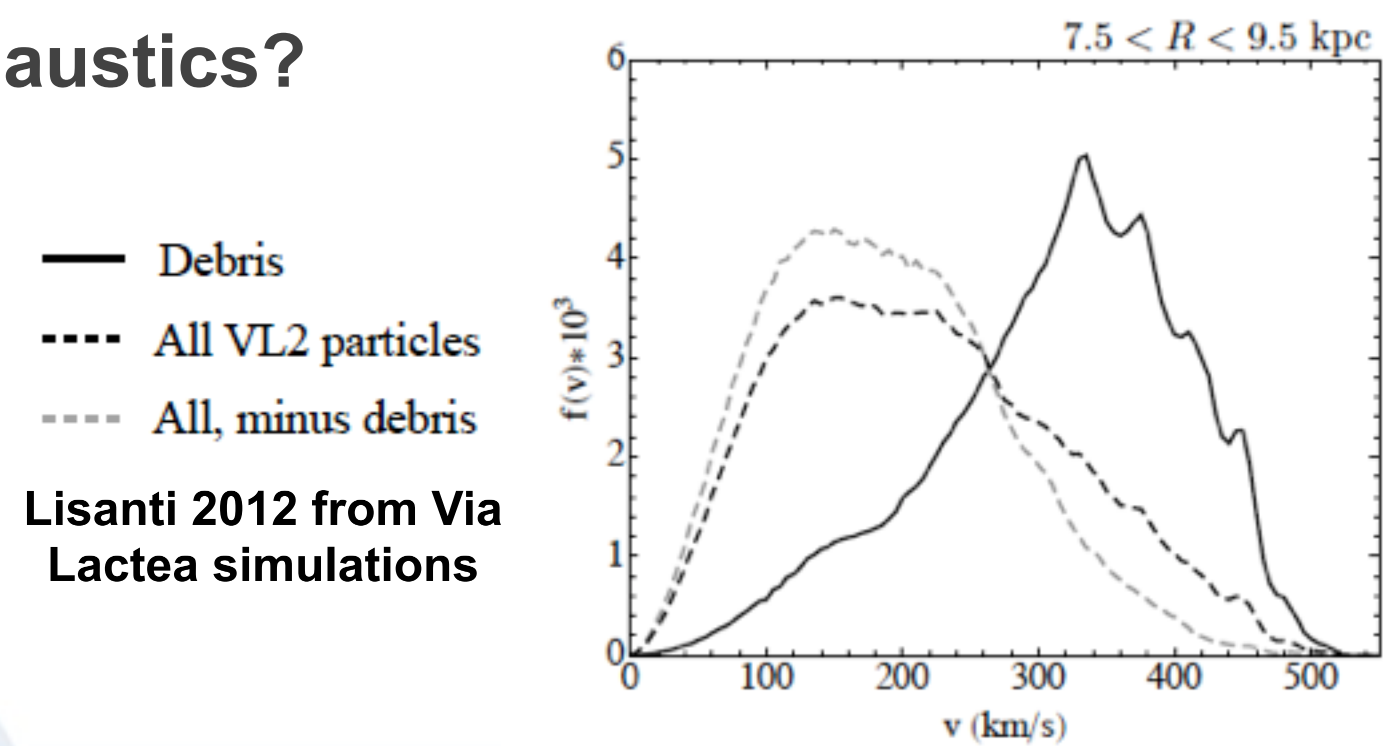
Aquarius 'Milky way' halo, res~0.05 kpc, 200 million particles

Simulations and Direct Searches

- **The Galaxy:** How well do we know the 'smooth' Milky Way? Is NFW a good description? Models plus observations --
- **Substructure/Velocity Distribution:** What is the DM phase space distribution in our local neighborhood? Streams and debris flows yield more scattering at recoil energies where a Maxwellian would have a small contribution (but effects appear to be of order unity)
- **Caustics?**

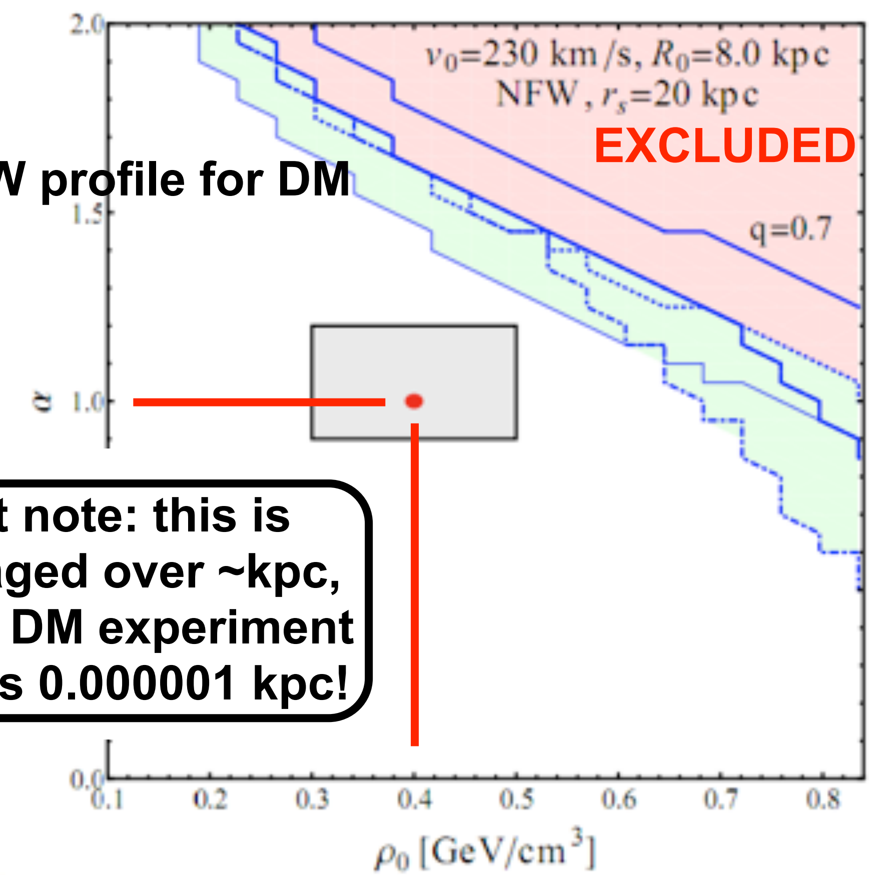


Iocco et al. 2011



Lisanti 2012 from Via Lactea simulations

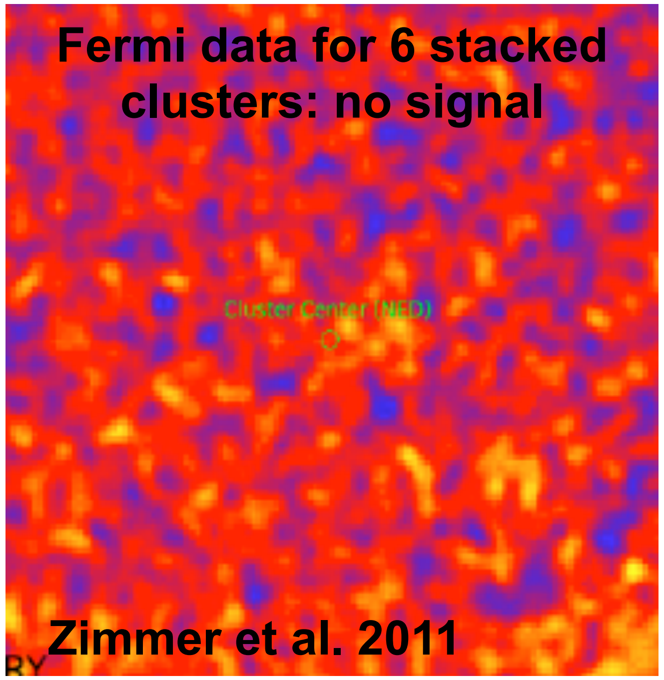
NFW profile for DM

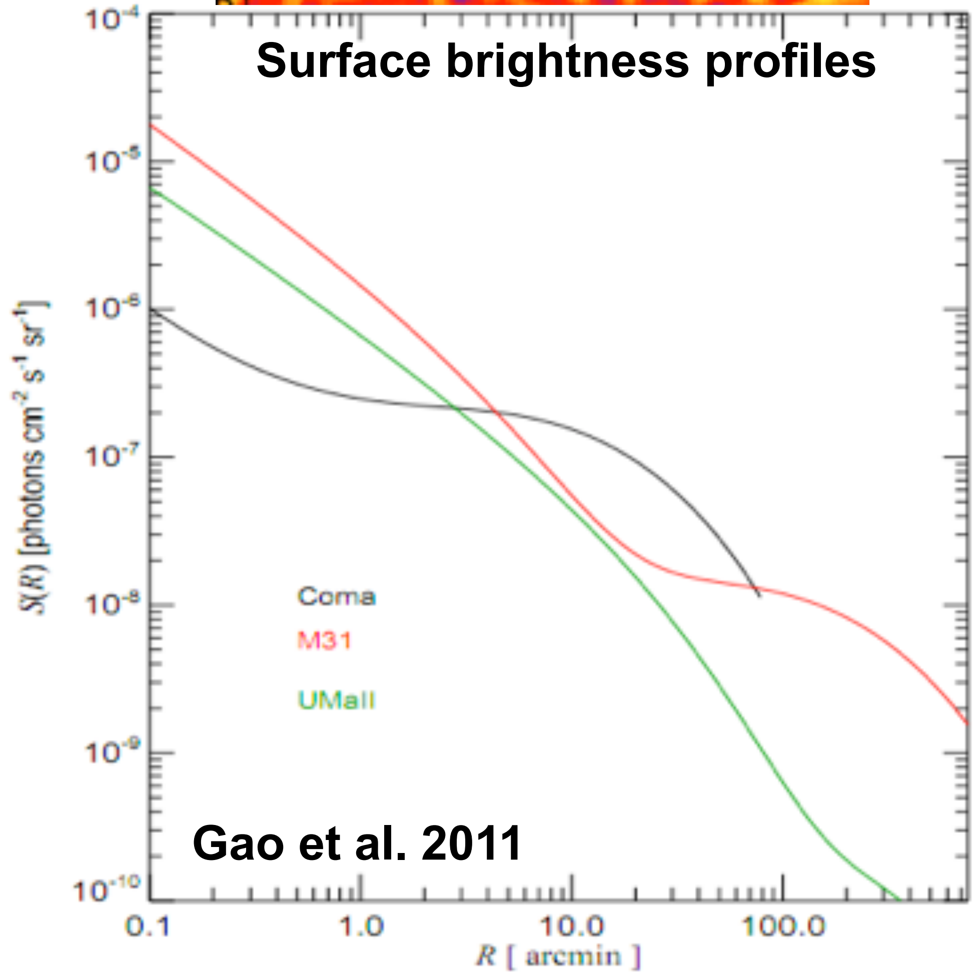


But note: this is averaged over ~kpc, direct DM experiment covers 0.000001 kpc!

Substructure and Indirect Searches

- **Indirect Detection:** Must understand details of DM halo distribution and nature of various uncertainties
- **Galactic Center:** Do we really know what's happening with DM near the center at <<1 kpc (baryons, black hole), yucky astrophysics (pulsars, clouds, supernova remnants, --)
- **Dwarf Spheroidals:** Uncertainties in DM profiles, stacking helps, relatively 'clean'; Fermi limits quite good, also Veritas
- **Galaxy Clusters:** Smooth component is close to NFW but substructure contribution somewhat uncertain; high end of boost factor is ~1000 from Phoenix simulations (but Fermi sees nothing), adventurous extrapolation to subhalo masses orders of magnitude smaller than those simulated





Summary

- **Unknowns:** Many assumptions made from structure formation are ‘spherical cow’; validity of severe extrapolations hard to establish; one-off nature of some observations difficult to compare to simulations
- **What Next:** Difficult to suggest future path in absence of DM detection; how to proceed with ‘continuous quality improvement’ in the absence of observational data? Where can simulations have maximal impact?
- **Inherent Limitations:** For many calculations, simulations are inherently limited; nature will have to be kind (e.g., possible existence of scaling relations that can be extrapolated?)
- **Any New Ideas?:** Structure formation much harder to tweak than particle physics models (unfortunately, theory is too well established), so future looks somewhat difficult --